Nanoscale Science and Engineering: Unifying and Transforming Tools

M.C. Roco
National Science Foundation, Arlington, VA 22230

and

Nanoscale Science, Engineering and Technology (NSET) Subcommittee, U.S. National Science and Technology Council

DOI 10.1002/aic.10087
Published online in Wiley InterScience (www.interscience.wiley.com).

Keywords: nanoscience, nanoengineering, NNI, science and engineering management, future trends, societal implications

Introduction

Nanoscale science and engineering activities are flourishing in the U.S. The National Nanotechnology Initiative (NNI) transforming plan proposed in 1999 led to a synergistic, accelerated and interdisciplinary development of the field, and motivated not only academic researchers but also industry and government organizations. This article presents the genesis of the National Nanotechnology Initiative, its current status and its likely evolution. It is argued that a main challenge and opportunity for engineering resides in design and manufacturing. Four generations of nanotechnology products and their respective manufacturing methods and research foci are identified: Passive nanostructures; active nanostructures; three-dimensional (3-D) nanosystems and systems of nanosystems; and heterogeneous molecular nanosystems. Designing new atomic and molecular assemblies is expected to increase in importance, including macromolecules "by design" nanoscale machines, and directed multiscale selfassembling. Although expectations from nanotechnology may be overestimated in short-term, the long-term implications on healthcare, productivity and environment appear to be underestimated.

What is Nanotechnology and Motivation

Nanotechnology is the ability to understand, control, and manipulate matter at the level of individual atoms and molecules, as well as at the "supramolecular" level involving clusters of molecules. Its goal is to create materials, devices, and systems with essentially new properties and functions because of their small structure. According to the National Nanotechnology Initiative (NNI), a more precise definition of the field includes three elements (Roco et al., 1999; NSET, 2001):

- Exploiting the new phenomena and processes at the intermediate length scale between single atom or molecule and about 100 molecular diameters, in the range of about 1 to 100 nanometers.
- With the same principles and tools to establish a unifying platform for science and engineering at the nanoscale. Figure 1 suggests this goal.
- Using the atomic and molecular interactions to develop efficient manufacturing methods.

There are at least three reasons for the current interest in nanotechnology. First, the research is helping us fill a major gap in our fundamental knowledge of matter. At the small end of the scale — single atoms and molecules — we already know quite a bit with tools developed by conventional physics and chemistry. At the large end, likewise, conventional chemistry, biology, and engineering have taught us about the bulk behavior of materials and systems. Until now, however, we have known much less about the intermediate nanoscale, which is the natural threshold where all living systems and man-made systems work. The basic properties and functions of material structures and systems are defined here, and even more importantly, can be changed as a function of the organization of matter via "weak" molecular interactions (such as, hydrogen bonds, electrostatic dipole, van der Waals forces, various surface forces, electro-fluidic forces, etc.). The intellectual drive toward smaller dimensions was accelerated by the discovery of size-dependent novel properties and phenomena. Only since 1981 have we been able to measure the size of an atom cluster on a surface (IBM, Zurich), and begun to provide better models for chemistry and biology selforganization and selfassembling. Ten years later, in 1991, we were able to move atoms on surfaces (IBM, Almaden). after 10 more years, in 2002, we assembled the molecules by physically positioning the component atoms. Yet, we cannot visualize or model with proper

M. C. Roco's e-mail address is mroco@nsf.gov. He is Chair of the NSET subcommittee, U.S. National Science and Technology Council.

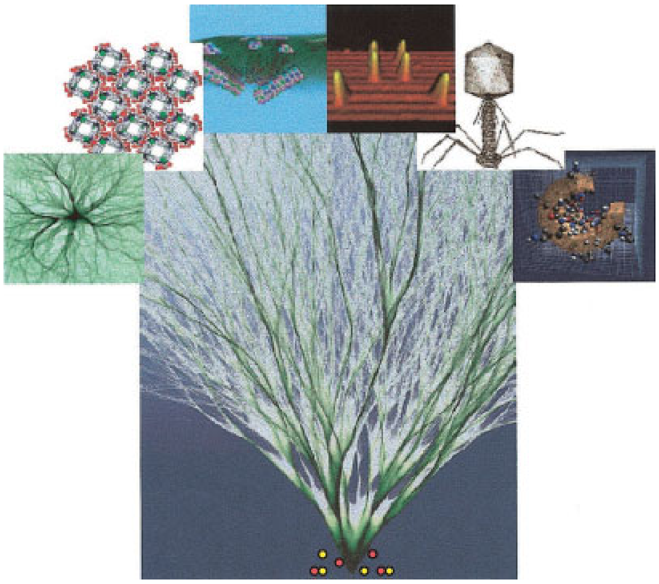

Figure 1. Broad implications from the same core nanoscale principles.

2-D flow of electrons from a nanoscale aperture, which is of relevance in nanoscale devices (Harvard University). The picture suggests broad ramifications of nanoscale science and engineering from the same core principles and vision into various disciplines and areas of application. These additional images courtesy of (left to right) Harvard University, Northwestern University, Scripps Research Institute, University of Southern California, Tufts University, and University of Illinois, Urbana-Champagne.

accuracy a chosen domain of engineering relevance at the nanoscale. We are still at the beginning of this road.

A second reason for the interest in nanotechnology is that nanoscale phenomena hold the promise of radically new applications and more effluent products. Possible examples include chemical manufacturing with designed molecular assemblies, processing of information using photons or electron spin, detection of chemicals or bioagents with only a few molecules, detection and treatment of chronic illnesses by subcellular interventions, regenerating tissue and nerves, enhancing learning and other cognitive processes by understanding the "society" of neurons, and cleaning contaminated soils with designed nanoparticles. With input from industry in the U.S., Asia Pacific countries, and Europe between 1997 and 1999, we have projected that $1 trillion in products and about $2 million jobs worldwide will be affected by nanotechnology by 2015 (Roco and Bainbridge, 2001). Extrapolating from information technology, where for every worker another 2.5 jobs are created in related areas, nanotechnology has the potential to create 7 million jobs overall by 2015 in the global market. Indeed, the first generation of nanostructured metals, polymers, and ceramics have already entered the commercial marketplace.

Finally, a third reason for the interest is the beginning of industrial prototyping and commercialization, and that governments around the world are pushing to develop nanotechnology as rapidly as possible. Coherent, sustained R&D programs in the field have been announced by Japan (April 2001), Korea (July 2001), EC (March 2002), Germany (May 2002), China (2002), and Taiwan (September 2002). However, the first and largest such program was the U.S. National Nanotechnology Initiative, announced in January 2000.

The NNI

The National Nanotechnology Initiative (NNI) is a long-term research and development program that coordinates 16 departments and independent agencies, with a total investment of about $961 million in fiscal year 2004 (Figure 2). It has become a top priority of the present and the past administration, as well as Congress, and it is a crosscut budget item at OMB, PCAST, and NRC. The program started formally in the fiscal year of 2001 (Oct. 2000), and was the result of activities going back to 1996. The "21st Century Nanotechnology R&D Act" was signed by Congress (Nov. 2003) and the President (Dec. 2003) recommending a structure of the investment, increase in funding, and the evaluation process. The Federal nanotechnology investment per agency since the beginning of NNI is given in Table 1. The main goals of NNI are:

- To extend the frontiers of nanoscale science and engineering through support for research and development;
- To establish a balanced and flexible infrastructure, including a skilled workforce;
- To address the societal implications of nanotechnology, including actions and anticipatory measures that should be undertaken in the society to bring sooner the advantage of the new technology and in a responsible way; and
- To establish a "grand coalition" of academe, industry and government to realize the full potential of the new technology. That is, develop a partnership between all participants, including collaboration between the nanoscale science and engineering providers (universities, national labs), nanotechnology products (various industries, medicine, environment) and nanotechnology funding sources (federal agencies, state and local organizations, including international dimension).

The initial driving force of the NNI was science (Roco et al., 1999). After 2002, however, technological innovation has risen in importance (NSTC, 2003). NNI investment in the period 2001–2003 was: academic institutions (65–70%), research laboratories (25–30%), and industry (about 5%). The allocation for R&D "grand challenges" is approximately the same as that for fundamental research, and it is expected to increase in importance in time. Industry has become a strong supporter,

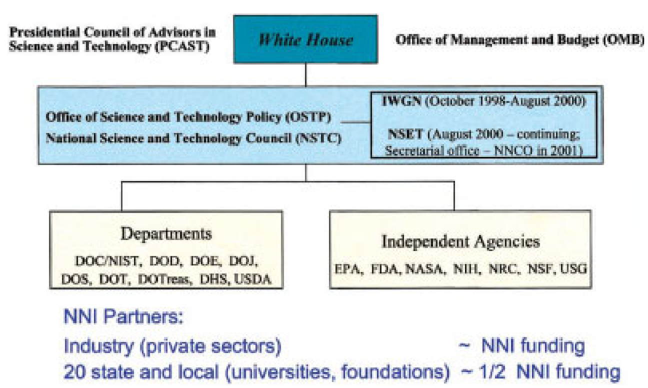

Figure 2. Organizations that have prepared and contribute to the National Nanotechnology Initiative (NNI).

Table 1. Contribution of Key Federal Departments and Agencies to NNI Investment

Federal Department or Agency	FY 1997 Actual ($M)	FY 2000 Actual ($M)	FY 2001 Actual ($M)	FY 2002 Actual ($M)	FY 2003 Actual ($M)	FY 2004 Enacted Congress ($M)	FY 2005 Request ($M)
National Science Foundation (NSF)	65	97	150	204	221	254	305
Department of Defense (DOD)	32	70	125	224	322	315	276
Department of Energy (DOE)	7	58	88	89	134	203	211
National Institutes of Health (NIH)	5	32	40	59	78	80	89
National Institute of Standards and Technology (NIST)	4	8	33	77	64	63	53
National Aeronautics and Space Administration (NASA)	3	5	22	35	36	37	35
Environmental Protection Agency (EPA)	—	—	6	6	5	5	5
Homeland Security (TSA)	—	—	—	2	1	1	1
Department of Agriculture (USDA)	—	—	1.5	0	1	1	5
Department of Justice (DOJ)	—	—	1.4	1	1	2	2
TOTAL (% of 2000)	116 (43%)	270 (100%)	465 (172%)	697 (258%)	862 (319%)	961 (356%)	982 (363%)

All budgets in $ million; each fiscal year (FY) begins on October 1 of the previous year and ends on September 30 of the respective year.

and its long-term R&D nanotechnology investment is expected to surpass the Federal NNI expenditures by next year. Also, over 20 states in the US have realized that nanotech has economic potential and in 2002 made a commitment for nanotechnology that is more than half the NNI annual budget. The worldwide government investment in nanotechnology in part stimulated by NNI is over $3 billion, a sevenfold increase as compared to about $430 million in 1997 (Figure 3).

Outcomes from the first three years of NNI

In its first three years (fiscal years 2001–2003), the NNI has changed the R&D landscape for nanotechnology research and education, advancing it from questions such as, "what is nanotechnology?" to "how can we take advantage of it faster?" In particular:

- Research toward the systematic control of matter at the nanoscale is advancing faster than envisioned in 2000. The time of reaching commercial prototypes has been reduced by at least a factor of two for key applications, such as detection of cancer, molecular devices, and special nanocomposites. Searching the "high impact articles" of the Institute for Scientific Information, Inc. provides a good indicator for publications. About 50% of the highly cited articles (citations after 2 years) in the most recent search (with *nano* in the title of the respective articles) originate from the U.S. After 3 years, in 2003, the NNI supports about 2,500 active awards in about 300 academic organizations, and about 200 small businesses and nonprofit organizations in all 50 states. An example of directed multiscale selfassembling is the planar array of gold nanoparticles by chaperonins ring structures, shown in Figure 4 (McMillan et al., 2002).

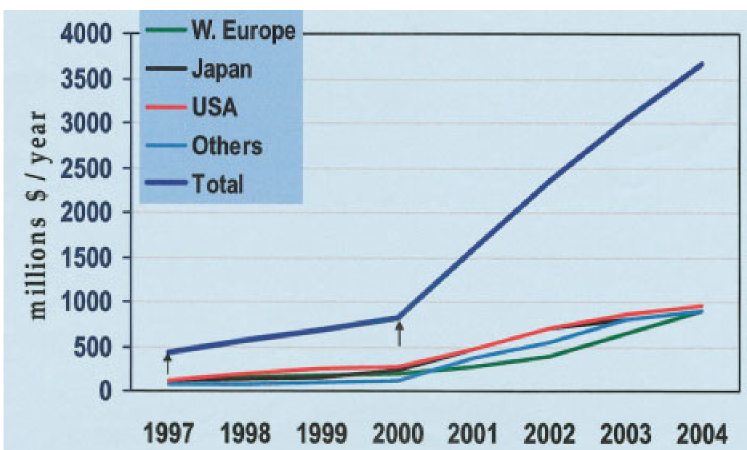

Figure 3. International context: Nanotechnology in the world government investments in the past seven years 1997–2004 (estimation NSF).

Explanatory notes: (a) "W. Europe" includes countries in EU and Switzerland; the rate of exchange $1 = 1.1 Euro until 2002; = 0.9 Euro in 2003, and = 0.8 Euro in 2004; Japan rate of exchange $1 = 120 yen in 2002, = 110 yen in 2003, = 105 yen in 2004; " Others " include Australia, Canada, China, Eastern Europe, FSU, Israel, Korea, Singapore, Taiwan and other countries with nanotechnology R&D; (b) A financial year begins in USA on October 1 of the previous calendar year, 6 months before in most other countries;(c) Estimates use the nanotechnology definition as defined in the NNI (this definition does not include MEMS and microelectronics), and include the publicly reported government spending.

• The NNI has already made the United States into a "power house"of nanoscale science and engineering, with about 40,000 researchers, students and workers qualified in at least one aspect of nanotechnology. Meanwhile, systemic changes are in preparation for undergraduate and K-12 education, by earlier introduction of nanoscience and reversing the "pyramid of science" with understanding of the unity of nature at the nanoscale from the beginning. In 2002, NSF announced the nanotechnology undergraduate education program (Program solicitation NSF 02–148), and in 2003, the nanotechnology high school and informal education program (Program solicitation NSF 03–044). In the next years, we plan to change the language of science even earlier and involve science museums to seed this language to K-12 students. About 7,000 students and teachers have been trained in 2003 with NSF support. All 250 major science and engineering colleges in the US have introduced educational activities related to nanoscale science and engineering in the last 3 years.

• Significant infrastructure has been established in over 60 universities with nanotechnology user capabilities. Five networks (NSF's Network for Computational Nanotechnology, National Nanotechnology Infrastructure Network, and Oklahoma Network for Nanotechnology; the DOE large facilities Nanoscale Science Research Centers; and the NASA nanotechnology academic centers) have been established. The remote use of experimental and educational facilities, as well as computational capabilities, is expanding.

• Industry investment has reached about the same level of investment as the NNI in the medium and long-term R&D, and almost all major companies in traditional and emerging fields have nanotechnology groups at least to survey the competition. For example, Intel has reported $20 billion revenues from products where nanotechnology plays a key role in 2003. Over ⅔ of the patents related to nanotechnology as recorded by the U.S. Patent and Trade Office in 2002 are from the U.S. (Huang et al., 2003), whereas the NNI funding is about 25% of the world government investment. About 75% of startup companies in nanotechnology established by the second part of 2003 are in the U.S. (about 1,100 of 1,500 worldwide, according to NanoBusiness Alliance). Despite the general economic downturn, nanotechnology venture funding in the U.S. doubled in 2002 as compared to 2001, and in the US there are more start-up companies than all other countries combined. The NNI needs to further encourage small businesses. For example, NSF supported more than 100 small businesses with an investment of $36 million between 2001 and 2003.

• The NNI's vision of a "grand coalition" of academe, government, industry and professional groups is taking shape. Over 22 regional alliances have been established throughout the US and develop local partnerships, support commercialization and education. Professional societies have established specialized divisions, organize workshops and continuing education programs, among them the American Association for the Advancement of Science, American Chemical Society, American Physics Society, Materials Research Society, American Society of Mechanical Engineers, American Institute of Chemical Engineers, Institute of Electrical and Electronics Engineers, and American Vacuum Society. The attention on nanotechnology implications is extending to the legislative and even judiciary branches of the U.S. Government.

• Societal implications were addressed from the start of the NNI, beginning with the first research and education program on environmental and societal implications, issued by NSF in July 2000. In September 2000, the report on "Societal Implications of Nanoscience and Nanotechnology" was issued. The interagency NSET established the National Nanotechnology Coordinating Office to monitor potential unexpected consequences of nanotechnology, and has periodical meetings on the environmental and health implications of nanoparticles. NSF has had five program announcements since July 2000, that included "Environmental Processes at the Nanoscale" and "Societal Implications" as research and education themes. Today, in 2004, the number of projects in the area has grown significantly, funded by NSF, EPA, NIH, DOE, and other agencies. The NNI crosscutting annual investment in nanoscale research with relevance to the environment is estimated at about $50 million in 2003, of which NSF awards over $30 million and EPA awards about $5 million. If one would add to this research for societal and educational implications, the investment is about 10% of the total annual NNI budget. For example, NSF has awarded over 100 projects with relevance to the environment, and several interdisciplinary groups address societal implications as those at UCLA and the University of South Carolina. Each of NSF's Nanoscale Science and Engineering Center has a research component on societal implications related to the topic of the respective center. In 2003, four relevant

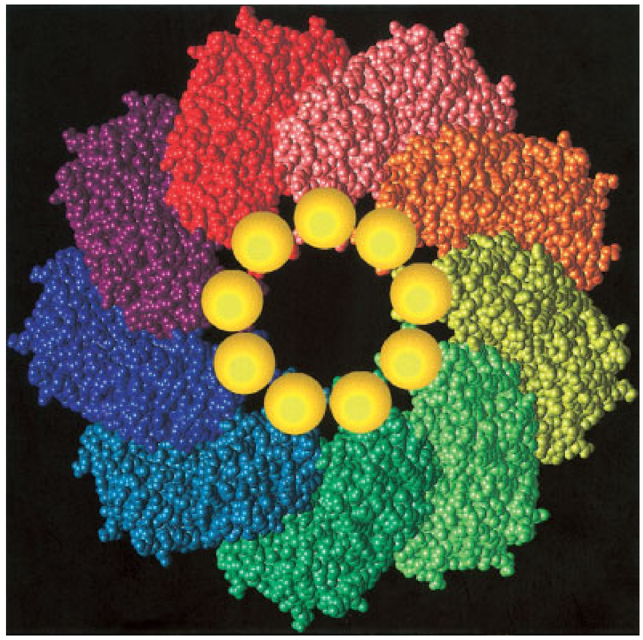

Figure 4. Selfassembled planar array of gold nanoparticles on a chaperonin protein template (R A McMillan, NASA).

A 17 nm genetically engineered protein cage called a chaperonin is used to organize nanoparticles into ordered arrays. In this example, gold arrays are formed by first tagging subunits with 1.4 nm nanoparticles and then selfassembling the subunits into the characteristic chaperonin ring structure. Extended ordered arrays can be formed because engineered chaperonins readily form 2-D crystals. The ability of the chaperonin to tolerate multiple genetic deletions and substitutions allows both the chemical functionality and the size of the pore leading into the core of the cage to be engineered. By tailoring the pore amino acid sequences, extended arrays of materials in addition to gold can be formed.

interagency workshops were held on environmental, medical and societal implications issues, and NSF and EPA had their own grantees conferences in 2002 and 2003 (see on the Web at www.nano.gov, www.nsf.gov/nano). Awareness of potential unexpected consequences of nanotechnology has increased, and Federal agencies meet periodically to discuss those issues.

New R&D potential targets for 2015

Seven potential nanoscale R&D developments expected by 2015 are:

- *Half of the newly designed advanced materials and manufacturing processes are built using control at the nanoscale.* The structure and function control still may be rudimentary in 2015 as compared to the long-term potential of nanotechnology. This will mark a milestone toward the new industrial revolution as outlined in 2000. The estimation is based on evaluations made with industry in a variety of sectors including electronics, chemicals, heavy industry, pharmaceutical, and aeronautics. Several challenges are listed below. Visualization and numerical simulation of 3-D domains with nanometer resolution will be necessary for engineering applications. Nanoscale designed catalysts will expand the use in "exact" chemical manufacturing to cut and link molecular assemblies, with minimal waste. Silicon transistors will reach dimensions smaller than 10 nm and will be integrated with molecular or other kinds of nanoscale systems (beyond or integrated with CMOS). One may recall that in 2000, we contemplated the "brick wall" of physical principles that would limit the advancement of silicon technology by the end of this decade. Now we are looking to advances in CMOS technology to extend another decade (by 2020) and then to its integration with bottom-up selfassembling. New science and engineering platforms may be developed, such as one based on carbon based chemistry, replacing transport of electron charge with electron spin, phase logic, creating photonic chips, with voltage interaction between electron and nuclei, and exploiting the coupling mechanisms between electric-magnetic-optical effects in solid state.
- *Suffering from chronic illnesses is being sharply reduced.* It is conceivable that by 2015, our ability to detect and treat tumors in their first year of occurrence might greatly mitigate suffering and death from cancer. In 2000, we aimed for earlier detection of cancer within 20–30 years. Today, on the basis of the results obtained during 2001–2003 in understanding the processes within a cell, as well as new instrumentation to characterize those cellular processes, the National Cancer Institute has included a nanotechnology group in trying to eliminate cancer as a cause of death if treated in a timely manner. Pharmaceutical synthesis, processing and delivery will be enhanced by nanoscale control, and about half of pharmaceuticals will use nanotechnology in a key component. Visualization of internal functions and modeling the brain based on neuron-to-neuron interactions will be possible with advances in nanoscale measurement and simulation.

The beginning of NNI

In November 1996, I organized a small group of researchers and experts from the government including Stan Williams (Hewlett Packard), Paul Alivisatos (University of California, Berkeley) and Jim Murday (Naval Research Laboratory), and we started to do our homework in setting a long-term plan for nanotechnology. We began with preparing supporting publications, including a report on research directions in 10 areas of relevance, despite the low expectation of additional funding at that moment. NNI was prepared with the same rigor as a science project between 1997 and 2000: we developed a long-term vision for research and development (Roco et al., 1999), we completed an international benchmarking of nanotechnology in academe, government, and industry (Seigel et al., 1999), we ran a program solicitation "Partnership in Nanotechnology: Functional Nanostructures" at NSF, and we received feedback from the academic community (1997–1998). Other milestones included a plan for the U.S. government investment (NSTC, 2000), a brochure explaining nanotechnology for the public (NSTC, 1999), and a report on the societal implication of nanoscience and nanotechnology (Roco and Bainbridge, 2001). More than 150 experts, almost equally distributed between academe, industry, and government, contributed in setting the nanotechnology research directions.

On behalf of the interagency group on March 11, 1999 in the historic Indian Hall at the White House's Office of Science and Technology Policy (OSTP), I proposed the NNI with a budget of half billion dollars for the fiscal year 2001. Although, other topics were on the agenda of that meeting, nanotechnology captured the imagination of those present, and discussions reverberated for about 2 h. It was the first time that a forum at this level with representatives from the major Federal R&D departments reached a decision to consider exploration of nanotechnology as a national priority. We had the attention of Neil Lane, then the Presidential Science Advisor, and Tom Kalil, then economic assistant to the President. However, few experts gave even a small chance to nanotechnology to become a national priority program. After March 2003, we focused our attention on the six major Federal department and agencies–the National Science Foundation (NSF), Dept. of Defense (DOD), Dept. of Energy (DOE), NASA, National Institutes of Health (NIH), and the National Institute of Standards and Technology (NIST) –that would place nanotechnology as a top priority during the summer of 1999. Then, the approval process moved to the Office of Management and Budget (OMB) (November 1999), Presidential Council of Advisors in Science and Technology (PCAST) (December 1999), and the Executive Office of the President (EOP, White House) (January 2000), and had supporting hearings in the House and Senate of the U.S. Congress (Spring 2000).

President Clinton announced the NNI at Caltech in Jan. 2000, beginning with words, such as "Imagine what could be done. . . ". In Aug. 2000, the White House advanced the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN, 1998–2000) to the level of the Subcommittee on Nanoscale Science, Engineering and Technology (NSET), with the charge of implementing the NNI. The National Nanotechnology Coordinating Office (NNCO) was established as a secretariat office to NSET in Jan. 2001. In fiscal years 2002 and 2003, NNI has increased significantly, from 6 to 16 departments and agencies, and an increased focused was given to instrumentation, manufacturing methods, and biochemical detection. The Presidential announcement of NNI with its vision and program motivated and partially stimulated the international community. About another 40 countries have announced priority nanotechnology programs since the NNI announcement. It was as if nanotechnology had gone through a phase transition: what had once been perceived as blue sky research of limited interest (or in the view of several groups, science fiction, or even pseudoscience), was now being seen as a key technology of the 21st century. After initially passing the House with a vote of 405–19 (H.R. 766), and then the Senate with unanimous support (S. 189) in November 2003, the "21st Century Nanotechnology R&D Act" was signed by President Bush on December 3, 2003. The bipartisan support is strong because the nanotechnology progress is seen as "a higher purpose" beyond party affiliation.

• *Science and engineering of nanobiosystems will become essential to human healthcare and biotechnology*. This area is one of the most challenging and fastest growing components of nanotechnology. It is essential for a better understanding of living systems, and for developing new tools for medicine and solutions for healthcare (such as synthesis of new drugs and their targeted delivery, regenerative medicine, and neuromorphic engineering). Important challenges are understanding processes inside a cell and the neural system. Nanobiosystems are a source of inspiration and provide models for man-made nanosystems. Research may lead to better biocompatible materials and nanobiomaterials for industrial applications.

• *Converging science and engineering from the nanoscale will establish a mainstream pattern for applying and integrating nanotechnology with biology, electronics, medicine, learning and other fields.* It includes hybrid manufacturing, neuromorphic engineering, artificial organs, expanding life expectancy, increased productivity, enhancing learning and sensorial capacities. New concepts will be developed in distributed manufacturing and multicompetency clustering. The confluence of nanoscience with biology, information and cognitive sciences will contribute to unifying concepts in science, engineering, technology, medicine, and agriculture.

• *Life-cycle sustainability and biocompatibility will be pursued in the development of new products.* Knowledge development in nanotechnology will lead to reliable safety rules for limiting unexpected environmental and health consequences of nanostructures. Synergism among life-cycles of various groups of products will be introduced for overall sustainable development. Control of contents of nanoparticles will be performed in air, soils, and waters with a national network.

• *Knowledge development and education will originate from the nanoscale instead of the microscale.* Earlier nanoscience education will change the role of science and motivation for schoolchildren. A new education paradigm not based on disciplines, but on unity of nature and education-research integration will be tested for K-16 (reversing the pyramid of learning (Roco, 2003b)). Science and education paradigm changes will be at least as fundamental as those during the "microscale S&E transition" that originated in the1950s where microscale analysis and scientific analysis were stimulated by the space race and digital revolution. The new "nanoscale S&E transition" will change the foundation of analysis and the language of education stimulated by the nanotechnology products. The basic concepts needed for converging new technologies need to be introduced earlier in education, beginning with K-12.

• *Nanotechnology businesses and organizations will restructure toward integration with other technologies, distributed production, continuing education, and forming consortia of complementary activities.* Traditional and emerging technologies will be equally affected. Manufacturing will focus on local outlets remotely controlled, with multifunctional and clustered capabilities. The legal system will coevolve with the new technology affecting on an increasing rate human potential, collective behavior, and human-machine interface.

Engineering Perspective: Four Generations of Nanotechnology Applications

Engineering research and education, including chemical engineering, plays a key role in nanomanufacturing, and this role will expand in the future because of its integrative, system approach oriented and transforming characteristics. This role will be essential as the degree of complexity of systems increases at the nanoscale, and various disciplines of science and engineering converge. The rudimentary capabilities of nanotechnology today for systematic control and manufacture at the nanoscale are envisioned to evolve in four overlapping generations of new nanotechnology products with different areas of R&D focus. Each generation of products is marked by the creation of commercial prototypes with systematic control of the respective phenomena and manufacturing processing.

(a) **First Generation of products (~2001-): passive nanostructures,** illustrated by nanostructured coatings, dispersion of nanoparticles, and bulk materials - nanostructured metals, polymers, and ceramics. The primary research focus is on nanostructured materials and tools for measurement and con-

NNI modes of support

The NNI funding strategy is based on five modes of investment. The first mode supports a balanced investment in fundamental research across the entire breadth of science and engineering, and it is lead by NSF.

The second mode, collectively known as the "grand challenges," focuses on nine specific R&D areas that are more directly related to applications of nanotechnology, and that have been identified as having the potential to realize significant economic, governmental, and societal impact in about a decade. The nine "grand challenges" are

(1) Nanostructured materials by design (NSF is the lead agency)
(2) Manufacturing at the nanoscale (NIST and NSF - lead agencies)
(3) Chemical-biological-radiological-explosive detection, and protection (DOD - lead agency)
(4) Nanoscale instrumentation, and metrology (NIST and NSF – lead agencies)
(5) Nanoelectronics, -photonics, and -magnetics (DOD and NSF – lead agencies)
(6) Healthcare, therapeutics, and diagnostics (NIH – lead agency)
(7) Efficient energy conversion and storage (DOE – lead agency)
(8) Microcraft and robotics (NASA – lead agency)
(9) Nanoscale processes for environmental improvement (EPA and NSF – lead agencies)

The third mode of investment supports centers of excellence that conduct research within the host institution(s). These centers pursue projects with broad multidisciplinary research goals that are not supported by more traditionally structured programs. These centers also promote education of future researchers and innovators, as well as training of a skilled technical workforce for the growing nanotechnology industry. NSF, DOD and NASA have established 16 new research centers in 2001–2003.

The fourth mode funds the development of infrastructure, instrumentation, standards, computational capabilities, and other research tools necessary for nanoscale R&D. NSF established three research and used facility networks, and DOE a large-scale user facility network.

The fifth and final mode recognizes and funds research on the societal implications, and addresses educational needs associated with the successful development of nanoscience and nanotechnology. Besides the graduate and postgraduate education activities, NSF supports nanoscale science and engineering programs for earlier nanotechnology education for undergraduates, high schools, and public outreach.

trol of nanoscale processes. Examples are research on nanobiomaterials, nanomechanics, nanoparticle synthesis and processing, nanolayers and nanocoatings, various catalysts, nanomanufacturing of advanced materials, and interdisciplinary simulation and experimental tools. Most of the industrialized countries have introduced products in the last 2–3 years, from paints and cosmetics (Australia) to car components (Germany, Japan, US) and nanostructured hard coating and filters (U.S.). China has made significant efforts in reaching this relatively large market.

(b) **Second Generation of products (~2005 -): active nanostructures,** illustrated by transistors, amplifiers, targeted drugs and chemicals, actuators, and adaptive structures. An increased research focus will be on novel devices and device system architectures. Key areas or research include nanobiosensors and devices, tools for molecular medicine and food systems, multiscale hierarchical modeling and simulation, energy conversion and storage, nanoelectronics beyond CMOS, 3-D nanoscale instrumentation and nanomanufacturing, R&D networking for remote measurement and manufacturing, converging technologies (nano-bio-info-cogno) and their societal implications. The convergence of nanotechnology with information technology, modern biology, and social sciences will reinvigorate discoveries and innovation in almost all areas of the economy. Support technological innovation and research dissemination will play an important role in the NNI investments to address new areas of research, and the increased role of engineering as the development of tools and manufacturing methods increases in importance. Illustrations are the research on 5 nanometer CMOS, nanophotonics and sensors. Most of the Pacific Rim countries, and particularly Japan, Korea, and Taiwan, are raising in capturing segments of this market, whereas the U.S. and European countries also have significant discoveries and innovations in active nanostructures.

(c) **Third Generation (~2010 -): 3-D nanosystems and systems of nanosystems** with various syntheses and assembling techniques, such as bioassembling; networking at the nanoscale and multiscale architectures. Research focus will shift toward heterogeneous nanostructures and supramolecular system engineering. This includes directed multiscale selfassembling, artificial tissues and sensorial systems, quantum interactions within nanoscale systems, nanostructured photonic devices, scalable plasmonic devices, chemico-mechanical processing, and nanoscale electromechanical systems (NEMS), and targeted cell therapy with nanodevices. The U.S. has an advantage in heterogeneous nanosystems and systems of nanosystems research in part because of its strength in fundamental research and medical areas. European and Pacific Rim countries develop centers of excellence in this area.

(d) **Fourth Generation (~2015 -): heterogeneous molecular nanosystems,** where each molecule in the nanosystem has a specific structure and plays a different role. Molecules will be used as devices and from their engineered structures and architectures will emerge fundamentally new functions. This is approaching the way biological systems work, but biological systems are in water, process the information relatively slow, and generally have more hierarchical scales. Research focus will be on atomic manipulation for design of molecules and supramolecular systems, dynamics of single molecule, molecular machines, design of large heterogeneous molecular systems, controlled interaction between light and matter with relevance to energy conversion among others, exploiting quantum control, emerging behavior of complex macromolecular assemblies, nanosystem biology for healthcare (Heath et al., 2003) and agricultural systems, human-machine interface at the tissue and nervous system level, and convergence of nano-bio-info-cognitive domains. Examples are creating multifunctional molecules, catalysts for synthesis and controlling of engineered nanostructures, subcellular interventions, and biomimetics for complex system dynamics and control. All developed countries have incipient research on some of these topics with promise in the long term. Because the path from fundamental discovery to nanotechnology applications takes about 10–12 years in recent nanotechnology developments (that is, from the first article to the market: 9 years for giant magneto resistance, 12 years for cooper interconnect, 12 years for photoresists, 12 years for magnetic RAM), now is the time to begin exploratory research in heterogeneous molecular nanosystems and systems of nanosystems.

"Nanotechnology" in Support of General Science and Engineering, Education, and Human Potential

Nanotechnology is becoming a key national "competency" helping existing industry to become more efficient and competitive, advancing knowledge and education, supporting emerging technologies, and developing unprecedented products and medical procedures that could not be realized with existing knowledge and tools. A main reason for the development of NNI has been the vision based on intellectual drive toward exploiting new phenomena and processes, developing a unified science and engineering platform from the nanoscale, and with the molecular and nanoscale interactions for efficient manufacturing. Nanotechnology has the long-term potential to bring revolutionary changes in society and harmonize international efforts toward a higher purpose than just advancing a single field of science and technology, or a single geographical region. A global strategy guided by broad societal goals of mutual interest is envisioned.

A main reason for developing nanotechnology is to extend the limits of sustainable development. One way is "exact" manufacturing at the nanoscale with small consumption of energy, water and materials, as well as minimized waste. Another way is reducing the effects of existing nanostructured contaminants from traditional activities, such as combustion engines or from natural sources, such as biomineralization and sediment fragmentation. A third way is controlling the evolution of existing and newly released nanostructures in the environment. NNI's role is to provide R&D support for knowledge development, technological innovation and infrastructure, as well as identify possible risks for health, environment and human dignity, and inform the public with a balanced approach about the benefits and potential unexpected consequences.

Nanotechnology has the potential to change our comprehension of nature and life, and develop unprecedented manufacturing tools and medical procedures. It has broad relevance across science and engineering domains similar to information technology. Nanoscale science and engineering provide the material foundation for converging technologies for improving human potential and developing new science and engineering platforms (Roco and Montemagno, 2004).

Acknowledgments

This article is based on my experience in coordinating the NNI. Opinions expressed here are those of the author and do not necessarily reflect the position of NSET or NSF.

Literature Cited

Heath, J. R., M. E. Phelps, and L. Hood, “NanoSystems Biology,” *Molecular Imaging and Biology*, **5**(5), 312 (2003).

Huang Z., H. Chen, A. Yip, G. Ng, Z. K. Guo, and M. C. Roco, “Longitudinal Patent Analysis for Nanoscale Science and Engineering: Country, Institution and Technology Field,” *J. Nanoparticle Res.*, **5**(3–5), 333 (2003).

McMillan, R. A., C. D. Paavola, , J. Howard, S. L. Chan, N. J. Zulazec, and J. D. Trent, “Ordered Nanoparticle Arrays on Engineered Chaperonin Protein Templates,” *Nature Materials*, **1**(4), 247 (2002).

NSTC (National Science and Technology Council), *Nanotechnology - Shaping the World Atom by Atom* (Brochure for the public). Washington DC, available on the Web at http://www.wtec.org/loyola/nano/IWGN.Public.Brochure/ (1999).

NSTC, *National Nanotechnology Initiative: The Initiative and its Implementation Plan*, Washington DC, 142 pp, available on the Web at http://www.nano.gov/nni2.pdf (2000).

NSTC, National Nanotechnology Initiative: Supplement to the President’s FY Budget, Washington DC (2004).

Roco M. C., R. S. Williams, and P. Alivisatos, eds., *Nanotechnology Research Directions,* U.S. National Science and Technology Council, Washington DC (also published in 2000 by Kluwer Academic Publishers, Boston, 316 pp); available on the Web at http://www.wtec.org/loyola/nano/IWGN.Research.Directions/ (1999).

Roco, M. C., and W. Bainbridge, eds., *Societal Implications of Nanoscience and Nanotechnology,* National Science Foundation Report (also published by Kluwer Academic Publishers, Boston; 370 pp); available on the Web at http://www.wtec.org/loyola/nano/SocietalImplications/ (2000).

Roco, M. C., and W. S. Bainbridge, eds., *Converging Technologies for Improving Human Performance*, NSF-DOC Report (also published in 2003 byKluwer Academic Publishers, Boston, 468 pp) (2003).

Roco, M. C., and C. D. Montemagno, eds., *The Coevolution of Human Potential and Converging Technologies,* Annals of the New York Academy of Sciences, Vol. 1013 (2004).

Roco, M. C., “Broader Societal Issues of Nanotechnology,” *J. Nanoparticle Res.*, **5**(3-4), 181 (2003a).

Roco, M. C., “Converging Science and Technology at the Nanoscale: Opportunities for Education and Training,” *Nature Biotech.*, **21**(10), 1247 (2003b).

Siegel, R. W., E. Hu, and M. C. Roco, eds., *Nanostructure Science and Technology*. NSTC, Washington DC (also published in 1999 by Kluwer Academic Publishers, Boston, 336 pp); available on the Web at http://www.wtec.org/loyola/nano/ (1999).

U.S. Congress, 21st *Century Nanotechnology Research and Development Act*, S.189 (to become Public Law 108–153, signed by President G. W. Bush on December 3, 2003), Washington DC (Nov. 2003).